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New Processing Techniques for Aluminum Alloys

Frankford Arsenal

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The Materials Engineering Division at Frankford Arsenal is involved in an extensive research and development effort aimed at upgrading the properties of high strength aluminum alloys through the development of new processing techniques. Three areas of the work are presented. The first is concerned with solidification processing. Data are presented which show that, by eliminating the second phase particles, the mechanical properties of high strength aluminum alloys are improved, especially in the short transverse direction. The second area involves the development of new techniques for processing aluminum alloy ingots so that the resulting wrought products have a much finer grain size than that of conventionally processed material. Results are given which show that the specially processed fine grain material has better ductility and toughness than conventionally processed material at equivalent strength levels. The final area deals with thermal mechanical processing of wrought products. A new thermal mechanical treatment is described which enables one to produce aluminum alloys having a better combination of strength and ductility than is possible with conventional processing.

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New Processing Techniques for Aluminum Alloys

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ABSTRACT

The Materials Engineering Division at Frankford Arsenal is involved in an extensive research and development effort aimed at upgrading the properties of high strength aluminum alloys through the development of new processing techniques. Three areas of the work are presented. The first is concerned with solidification processing. Data are presented which show that by eliminating the second phase particles, the mechanical properties of high strength aluminum alloys are improved, especially in the short transverse direction. The second area involves the development of new techniques for processing aluminum alloy ingots so that the resulting wrought products have a much finer grain size than that of conventionally processed material. Results are given which show that the specially processed fine grain material has better ductility and toughness than conventionally processed material at equivalent strength levels. The final area deals with thermal mechanical processing of wrought products. A new thermal mechanical treatment is described which enables one to produce aluminum alloys having a better combination of strength and ductility than is possible with conventional processing.

INTRODUCTION

Although high strength aluminum alloys are used in Army materiel because of their light weight, ease of fabrication and good mechanical properties, their utilization in Army components could be substantially increased if high strength aluminum alloys having improved ductility and good secondary properties could be developed. This is especially true in thick sections. Over the past years Frankford Arsenal has been conducting studies aimed at improving the strength and secondary properties of the 7000 series alloys through the use of improved processing techniques. This paper describes recent significant accomplishments in three areas of processing research on high strength aluminum alloys: (1) solidification and homogenization, (2) ingot processing and (3) thermal mechanical treatments.

SOLIDIFICATION AND HOMOGENIZATION

The strength and ductility of commercial high strength wrought aluminum alloys are impaired by the presence of undissolved phases in the microstructure. These phases arise from two sources: insoluble impurity phases and soluble phases that were not dissolved due to inadequate homogenization treatments. Studies at Frankford Arsenal[1,2,3] and under contract with Professor M. C. Flemings of M.I.T.[4,5,6] have shown that eliminating the undissolved phases through control of purity, ingot solidification rates and homogenization treatments has led to alloys with improved properties.

The work was carried out on the 7000 series aluminum alloys, primarily 7075 (Al-5.6% Zn-2.5% Mg-1.6% Cu),[7] but the results are

applicable to the 2000 and 6000 series alloys as well. It was found that the amount of undissolved phases in the microstructure could be significantly reduced by (1) low impurity content (2) small dendrite arm spacing (DAS) in the ingot (3) proper homogenization time and temperature and (4) mechanical working of the ingot.

Studies showed that the insoluble impurity phases are mainly iron-rich due to the extremely limited solubility of iron in aluminum.[1] Thus, in the research, iron was limited to 0.01%.[2] Silicon was also limited to less than 0.01% as a precautionary measure since it also has low solubility in aluminum.[2] The specifications for commercial 7075 permit up to 0.5% max. iron and 0.4% max. silicon.[7]

The DAS is an important parameter affecting the kinetics of dissolution of the undissolved soluble phases because it is a measure of the diffusion distance and hence, the time involved in the homogenization process.[1] The finer the DAS the shorter the time required for dissolution of the material. It was found that if the DAS is greater than 100 microns, complete dissolution of the soluble phases will not be achieved in reasonable times. By maintaining proper control of the casting procedures to achieve rapid local solidification rates, i.e. by using direct chill casting techniques, a very small DAS can be produced even in large ingots.

To achieve a structure that is completely free of undissolved soluble phases, the homogenization temperature must be chosen so that the composition of the alloy is in the aluminum-rich solid solution phase field. In the experiments on 7075, a homogenizing temperature of 900°F

produced a completely homogeneous material, i.e. a material free of undissolved soluble phases.[1]

Mechanical working of the ingot at an elevated temperature prior to or as part of the homogenization treatment was found to decrease the time required for complete homogenization.[4] In fact, the greater the mechanical work, the less the time required for homogenization because the working decreases the diffusion distance between the second phase particles.

Figure 1 shows the longitudinal, transverse and short transverse microstructures of commercial and specially processed (homogeneous) 7075-T6 plate.[2] Note the absence of the second phase in the homogenized material. The tensile properties of these materials for 2 in. thick plate are shown in Figure 2.[2] It can be seen that the strengths of the materials are about the same whereas the ductility, as measured by reduction in area, of the homogeneous material is much greater than that of its commercial counterpart. This difference is especially notable in the short transverse direction. The properties of the homogeneous material are essentially isotropic whereas there is considerable directionality present in the properties of the commercial material.

The properties of several 7075-T6 2 in. thick plate, each containing a different amount of undissolved second phase, were documented.[3] The materials examined included a commercial plate and one containing no undissolved second phase. The completely homogeneous 7075 plate was treated by heating 48 hrs/860^{o}F + 48 hrs/900^{o}F, quenched and aged to the T6 temper. The other plate materials examined were homogenized for

various times at 860°F, quenched and aged to the T6 temper in order to vary the degree of undissolved second phase. The significant difference between the various 7075-T6 plate materials was the increase in reduction in area with decreasing amounts of undissolved second phase. (Figure 3). Similar results were obtained on 0.030 in. thick 7075-T6 sheet.[5] It was also found that in 7075-T6 sheet the strength increases with increasing degree of homogenization because of the increase in the concentration of solute elements in the matrix.[5]

Secondary properties such as fracture toughness and fatigue strength are improved by homogenization, especially in the short transverse direction.[3] (Figures 4, 5 and 6). Specifically, the plane strain fracture toughness in the short transverse direction in 2 in. thick 7075-T6 plate is 22,000 psi $\sqrt{\text{in.}}$ for commercial material and 40,000 psi $\sqrt{\text{in.}}$ for completely homogeneous material.[3] The fatigue strength in the short transverse direction in commercial 7075-T6 is 22,000 psi and is 27,000 psi in homogeneous 7075-T6[3]. It is interesting to note that the fatigue strengths of the two materials are equal in the longitudinal direction; their value is 27,000 psi showing that the fatigue strength of homogeneous 7075-T6 appears to be isotropic.

INGOT PROCESSING

Work carried out by Istituto Sperimentale dei Metalli Leggeri (ISML) (Milan, Italy) under a US/Italy Cooperative Research Program on Aluminum Alloys[8] showed that properties related to ductility, such as elongation, reduction in area and toughness are improved by the use of an intermediate thermal mechanical treatment (ITMT) designed to produce a wrought product

with grains that are finer than those obtained by conventional processing. Preliminary work has also indicated that ITMT processed forged plate may exhibit improved stress corrosion resistance.[9] Realizing the potential advantages of ITMT, a program was initiated at Frankford Arsenal to investigate the effect of the ISML technique as well as alternate procedures of ingot processing on the structure and properties of wrought aluminum products.[10, 11] In this paper the initial results obtained on wrought high purity homogeneous 7075 sheet and plate are presented. Work is in progress at Frankford Arsenal on a complete documentation of the effect of ITMT processing on the mechanical properties and secondary properties of 1 and 2 in. thick plate of such 7000 series alloys as 7075, 7075-Zr, X7007 and 7050 and such 2000 series alloys as 2024 and 2219.

ISML-ITMT involves a new concept in ingot processing in which ingots in a partially homogenized condition are worked at a relatively low temperature, recrystallized, homogenized and then conventionally worked (hot rolled) into wrought products. Since optimization of the ITMT process has not been completed at this time, materials have been examined in the as-recrystallized (AR) condition (a structure containing fine equiaxed grains) and the as-recrystallized + hot rolled (AR+HR) condition (a structure containing fine elongated grains) to determine the effect of grain morphology. Examples of the structures of AR and AR+HR+T6 ISML-ITMT 7075 sheet are shown in Figure 7.[10]

The key feature of the ISML-ITMT method is that the anti-recrystallizing element in the 7075 ingot, Cr, is maintained in supersaturated solid solution in the aluminum during both the partial homogenization

treatment and the low temperature deformation step making it ineffective in preventing recrystallization into a fine grain structure.[8] Following the recrystallization step, the Cr is precipitated during the homogenization treatment as the E phase ($Al_{18}Cr_2Mg_3$) to prevent grain growth or recrystallization during any subsequent processing of the ITMT material.[8] In contrast, recrystallization does not occur during conventional processing because in the early stages of processing the Cr is precipitated as the E phase along the original cast grain boundaries; this leads to coarse elongated grains.[8] (Figure 8).[10] Work at Frankford Arsenal also showed that if the Cr was precipitated prior to the initial deformation in the ISML-ITMT process, recrystallization into fine grains will not occur.[10,11]

Additional studies at Frankford Arsenal have indicated however that if the Zn, Mg and Cu are present as precipitate particles prior to the initial deformation it is possible to recrystallize 7075 into fine grain material even though the Cr is present as the E phase during the processing.[10,11] These studies led to the development of another ITMT method, FA-ITMT.[10,11] In this method, the Cr is precipitated out of solution by a long time homogenization treatment of the ingot and then the Zn, Mg, and Cu are precipitated out of solution by annealing the homogenized ingot prior to the initial deformation. The structure of FA-ITMT fine grain 7075 sheet in the AR and AR+HR+T6 conditions are shown in Figure 9.[10,11]

Initial work at Frankford Arsenal on ITMT plate has been limited to the production and evaluation of both ISML-and FA-ITMT 7075-T6 1 in.

thick plate in the as-recrystallized condition. (Figure 10 and 11).[11] Although there is a duplex structure in the AR ISML-ITMT 1 in. thick plate (Figure 10a) the overall grain structure is significantly finer than that of the commercial 7075-T651 1 in. thick plate (Figure 12). The grain size of the FA-ITMT material is also finer than that of the commercial 7075-T651. Increasing the recrystallization temperature to 960°F eliminated the duplex structure and produced fine equiaxed grains in the ISML-ITMT plate (Figure 10).[11]

The tensile properties of conventionally processed, ISML-ITMT and FA-ITMT homogeneous 7075-T6 sheet and plate are shown in Table I.[10,11] It can be seen that the fine grained ITMT 7075-T6 has equivalent strength and significantly better ductility than the conventionally processed material. Also, Table I clearly shows the added benefits to be gained by utilizing ITMT with the concepts of homogenization.

The stress corrosion tests of the ITMT and conventionally processed 7075-T6 1 in. thick plate indicate that the fine grained ITMT material may have a slightly better stress corrosion resistance than the conventionally processed material.[11] Additional testing is being conducted to verify these results.

Other work at Frankford Arsenal has shown the dependence of the tensile properties on the grain size of the wrought plate. (Figure 13)[11] It can be seen that there is only a slight dependence of the yield strength on grain size. Although this behavior is contrary to the usual strengthening effect of a fine grain size in pure metals and solid solution alloys, a negligible grain size dependence of the yield strength has also been reported in 2024-T4.[12] The pronounced dependence of the ductility on grain size in 7075-T6 can also be seen from Figure 13.

THERMAL MECHANICAL TREATMENTS

Thermal mechanical treatments as discussed in this section are those processes which combine thermal treatments and mechanical processing techniques to improve the properties of aluminum alloy mill products such as sheet and plate over those obtained in the standard T6 condition. (Solution heat treated, quenched and artificially aged). A common thermal mechanical treatment is the T8 temper which involves solution treating, quenching, cold working and then artificially aging. Since the cold work is applied prior to aging, the aging kinetics are affected. In the 2000 and 6000 series, the cold work accelerates the aging kinetics and the strength is greater than that in the T6 temper. The T8 temper is a commercial temper in these alloy systems. Cold work prior to aging does not have a favorable influence on the aging kinetics of 7000 series alloys and the strength in the T8 temper is no better than that in the T6 temper. For these reasons, T8 is not a commercially used temper in 7000 series alloys. The failure of the 7000 series alloys to respond favorably to cold work following solution heat treatment may be due to the fact that the 7000 series alloys harden in the T6 temper almost entirely by GP zones[13] and that cold work decreases the rate of G.P. zone formation.[14]

One means of raising the strength of the 7000 series alloys is the T9 temper. However, this temper is only a mechanical treatment which involves cold working the material in the T6 condition. In the T9 temper, the cold working does not influence the aging kinetics because the cold

work is applied after aging is essentially completed; the effects of aging and cold work are only additive. Cold working the T6 temper material does increase its strength, but the ductility of the material is greatly reduced. Also, since the T9 temper is not readily applied commercially, it is not used in the 7000 series alloys.

Based on the above information, ISML, under the US/Italy Cooperative Research Program previously mentioned, developed a new thermal mechanical treatment termed Final Thermal Mechanical Treatment (FTMT)[8,15] for 7000 series alloys, which gives better combinations of strength and ductility than can be obtained by the use of conventional treatments. Although FTMT was developed primarily for the 7000 series, it has been shown to give similar results for the 2000 and 6000 series alloys. FTMT consists of the application of plastic deformation between an initial and a final artificial aging step. That is, FTMT involves solution heat treatment, quench, natural age for 3 to 7 days , low temperature artificial age, cold work, and final artificial age either at a higher temperature than the first artificial aging step or for a longer time at the same temperature as the first artificial aging step. For example, in the FTMT of 7075 alloy the first artificial aging step is carried out at about 220°F, the working is 10 to 30% at room temperature (although working temperatures up to 375°F are acceptable), and the final artificial aging step is carried out in the temperature range of 220° to 250°F.[8]

The yield strength and corresponding elongation of several 7000 series commercial purity sheet alloys in the FTMT and T9 conditions are

plotted in Figure 14.[8,15] It can be seen that for a given treatment, T9 or FTMT, the strength increases and the elongation decreases. However, FTMT gives a better combination of strength and elongation than does the T9 temper; for a given strength, the elongation is greater in the FTMT than in the T9 temper and for a given elongation, the strength is greater in the FTMT than in the T9 temper.

Recent work at Frankford Arsenal has involved the application of FTMT to homogeneous plates of 7039, 7075, X7007 and X7050.[16] As can be seen from Table II the same benefits achieved in FTMT sheet are recognized in FTMT plate. Work on the effect of FTMT on the secondary properties of 7000 series alloys is in progress at Frankford Arsenal. It has been reported that extruded 7075 in the FTMT temper has better fatigue strength than extruded 7075-T6.[17]

There has been little research on the mechanisms involved in FTMT. However, on the basis of electron microscopy observations[8,15] and aging studies[14] it appears that the improvements achieved with FTMT are due to the presence of a finely distributed G.P. zone structure prior to deformation and the stability of the dislocation structure (produced by the deformation step) during the final aging step.

Although the work at Frankford Arsenal has involved the application of FTMT to produce material with substantially higher strength than T6 material, other recent work used FTMT to produce 7075 that will have the strength of the T6 temper and the stress corrosion immunity of the T73 temper.[18] With regard to the engineering applications of FTMT, Frankford Arsenal has successfully applied FTMT to small caliber

aluminum cartridge cases to obtain improved strength properties at critical locations in the cartridge case.[19]

SUMMARY

Recent work at Frankford Arsenal on upgrading the properties of high strength aluminum alloys through improved processing techniques is presented. The results show: (1) Elimination of the undissolved second phase by controlled solidification and homogenization techniques improves the mechanical properties of high strength aluminum alloys, especially in the short transverse direction, (2) New ingot processing techniques termed Intermediate Thermal Mechanical Treatments (ITMT)produce wrought aluminum alloy products that have a much finer grain size, significantly better ductility and at least equivalent stress corrosion resistance to conventionally processed materials at equivalent strength levels, (3) A new thermal mechanical treatment, Final Thermal Mechanical Treatment (FTMT), produces wrought high strength aluminum alloys that have a better combination of strength and ductility than is possible with conventional treatments.

By using controlled solidification and homogenization techniques in conjunction with the ITMT and FTMT processes, potential new avenues of approach are available for producing aluminum alloys with superior engineering properties.

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TABLE I - Long Transverse Tensile Properties of Homogeneous ITMT 7075-T6 Sheet (0.160 in. thick) and Plate (1 in. thick) (ref. 10, 11)

Material	Yield Strength (0.2% offset) ksi	Ultimate Tensile Strength ksi	Elongation %	Reduction in Area %
Sheet				
Conventional	69.8	83.3	12.8	31.1
ISML-ITMT	71.0	84.0	14.6	44.5
FA-ITMT	71.8	84.1	14.9	42.6
Plate				
Conventional*	72.8	82.5	9.5	15.0
Conventional	75.8	86.0	12.5	20.5
ISML-ITMT	73.7	83.2	18.2	29.6
FA-ITMT	73.9	83.0	19.0	35.1

* Commercial Purity

TABLE II - Longitudinal Tensile Properties of Homogeneous 7039, 7075, X7007 and X7050 Plate in the T6 and FTMT Tempers. (ref. 16)

Material	Yield Strength (0.2% offset) ksi	Ultimate Tensile Strength ksi	Elongation in 2 in. %	Reduction in Area %
7039-T6	49.1	60.2	12.7	35.2
7039-FTMT	69.4	76.6	9.2	17.2
7075-T6	78.7	87.0	11.0	14.0
7075-FTMT	87.0	92.4	8.4	14.0
X7007-T6	70.1	74.6	14.1	35.5
X7007-FTMT	80.5	84.0	9.3	15.6
X7050-T6	84.2	88.9	10.8	30.2
X7050-FTMT	92.1	97.7	8.6	27.6

FIGURE CAPTIONS

Figure 1. Longitudinal, transverse and short transverse microstructures of (a) commercial 7075-T6 and (b) specially processed 7075-T6 plate. (ref. 2)

Figure 2. Longitudinal, transverse and short transverse tensile properties of commercial 7075-T6 and specially processed 7075-T6 plate. (ref. 2)

Figure 3. Ductility characteristics of 7075-T6 aluminum alloy as a function of direction and second phase concentration. (ref. 3)

Figure 4. Relationship between the plane strain fracture toughness in the short transverse direction and the concentration of second phases of 7075-T6 aluminum alloy. (ref. 3)

Figure 5. Longitudinal fatigue characteristics of commercial and homogenized 7075-T6 aluminum alloy. (ref. 3)

Figure 6. Short transverse fatigue characteristics of commercial and homogenized 7075-T6 aluminum alloy. (ref. 3)

Figure 7. Microstructures of ISML-ITMT 7075 sheet. (a) as-recrystallized and (b) as-recrystallized + hot rolled + T6. Longitudinal sections. Mag. 100X. Keller's etch. (ref. 10, 11)

Figure 8. Microstructure of conventionally processed 7075-T6 sheet. Longitudinal section. Mag. 100X. Keller's etch. (ref. 10, 11)

Figure 9. Microstructures of FA-ITMT 7075 sheet. (a) as-recrystallized and (b) as-recrystallized + hot rolled + T6. Longitudinal sections. Mag. 100X. Keller's etch. (ref. 10, 11)

Figure 10. Microstructures of as-recrystallized ISML-ITMT 7075 1 in. thick plate. The material was recrystallized at (a) 860°F and (b) 960°F for 24 hrs and quenched. Longitudinal sections. Mag. 100X. Keller's etch. (ref. 11)

Figure 11. Microstructure of as-recrystallized FA-ITMT 7075 1 in. thick plate. Longitudinal section. Mag. 100X. Keller's etch. (ref. 11)

Figure 12. Microstructure of commercial 7075-T651 plate (1 in. thick). Longitudinal section. Mag. 100X. Keller's etch. (ref. 11)

Figure 13. The mechanical properties of 7075-T6 as a function of the reciprocal of the square root of the grain size measured from a longitudinal section in a direction perpendicular to the rolling direction. (ref. 11)

Figure 14. Yield strength and elongation of 7001, 7005, 7075 and 7139 alloys in the T6, T9 and FTMT tempers. (ref. 8, 15)

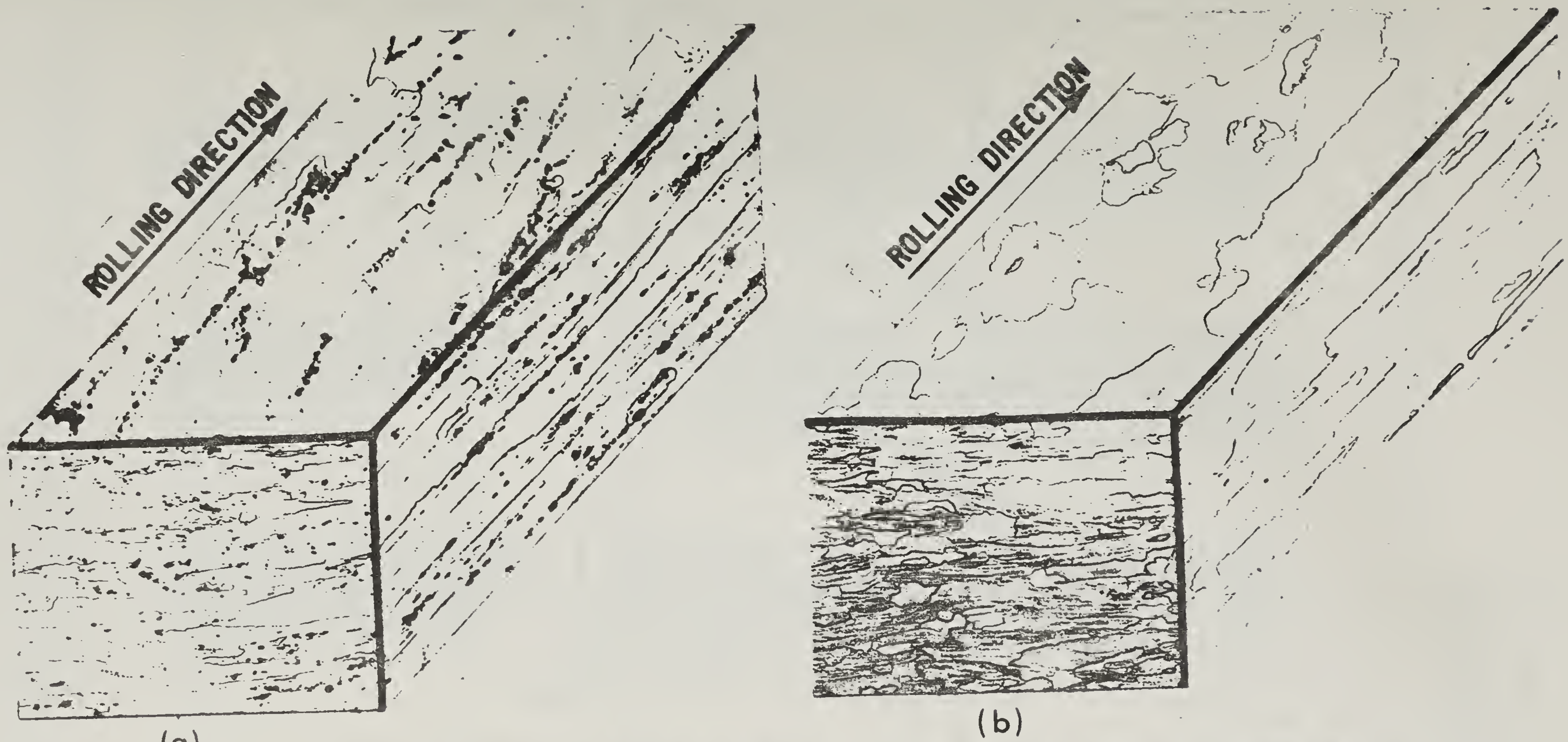


Figure 1. Longitudinal, transverse and short transverse microstructures of (a) commercial 7075-T6 and (b) specially processed 7075-T6 plate. (ref. 2)

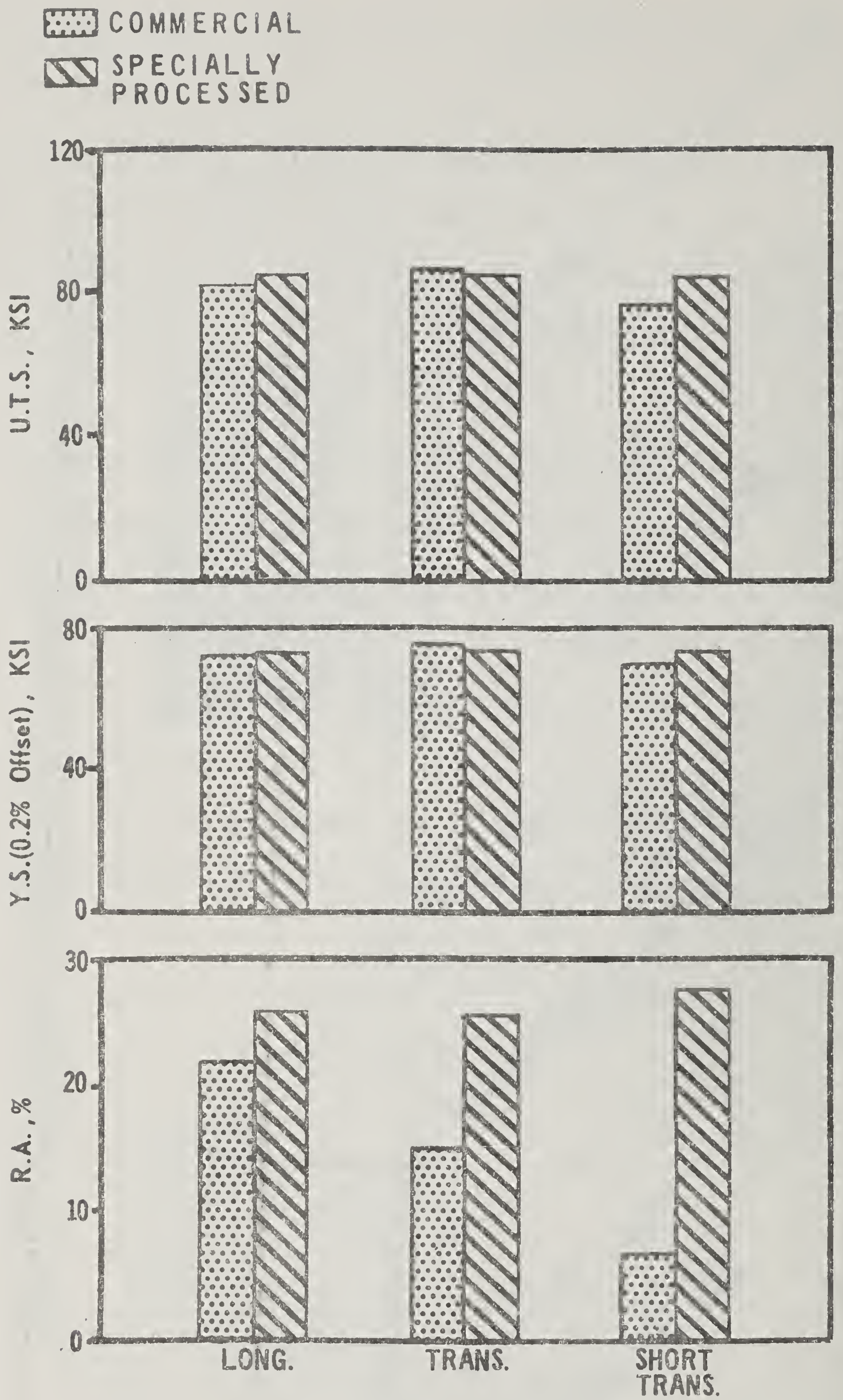


Figure 2. Longitudinal, transverse and short transverse tensile properties of commercial 7075-T6 and specially processed 7075-T6 plate. (ref. 2)

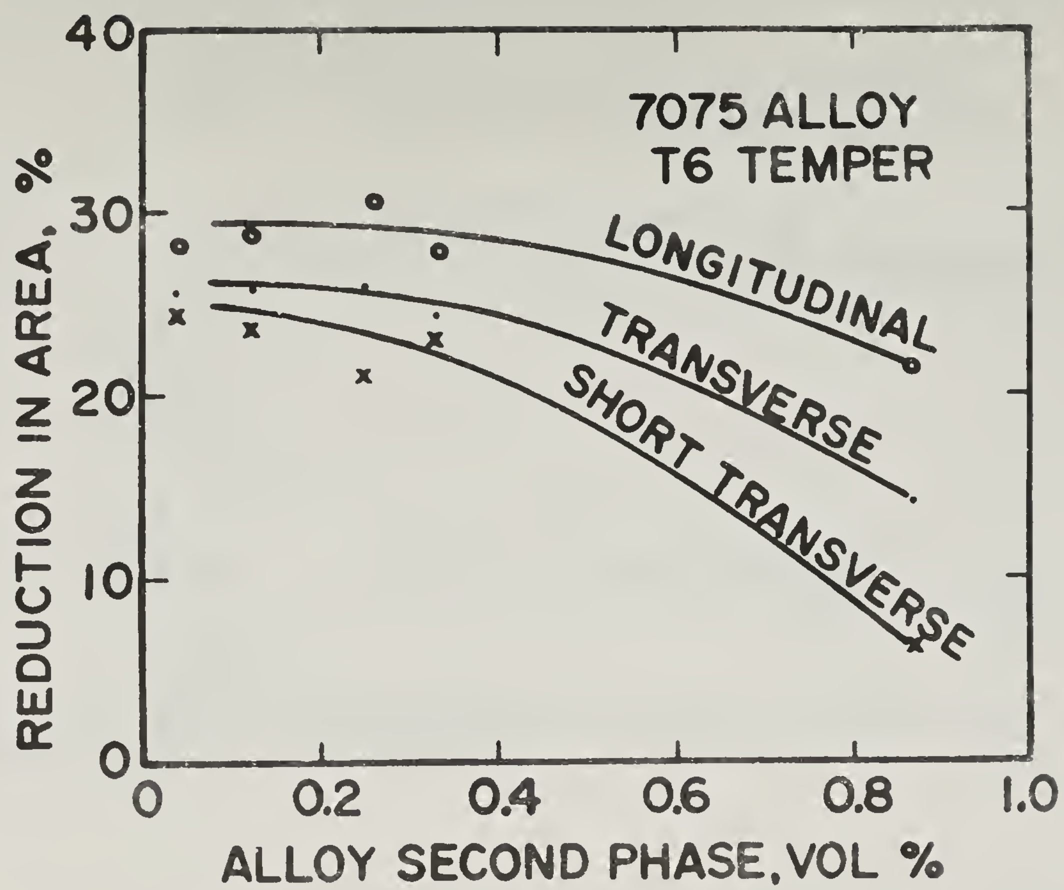


Figure 3. Ductility characteristics of 7075-T6 aluminum alloy as a function of direction and second phase concentration. (ref. 3)

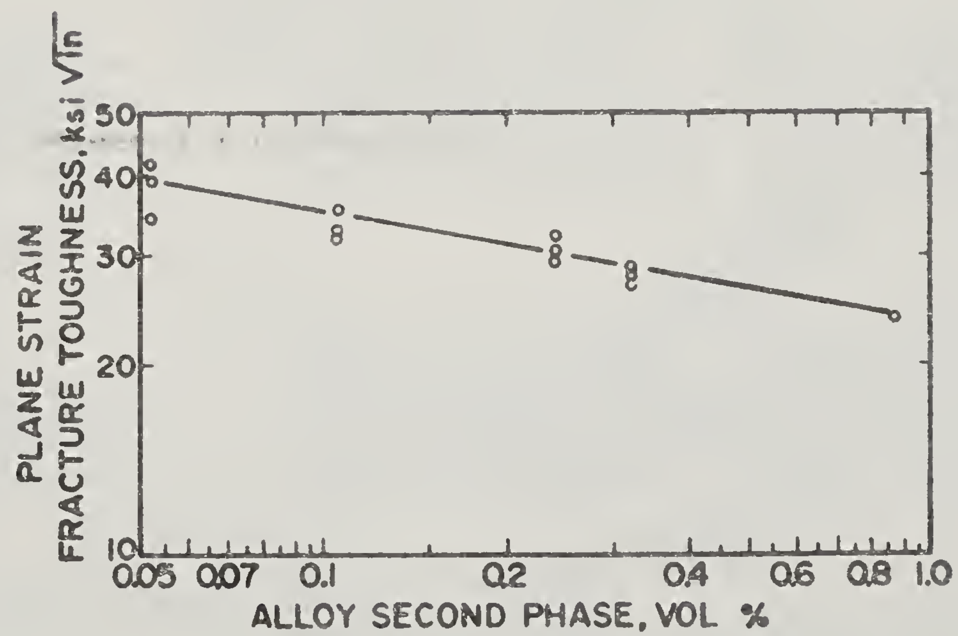


Figure 4. Relationship between the plane strain fracture toughness in the short transverse direction and the concentration of second phases of 7075-T6 aluminum alloy. (ref. 3)

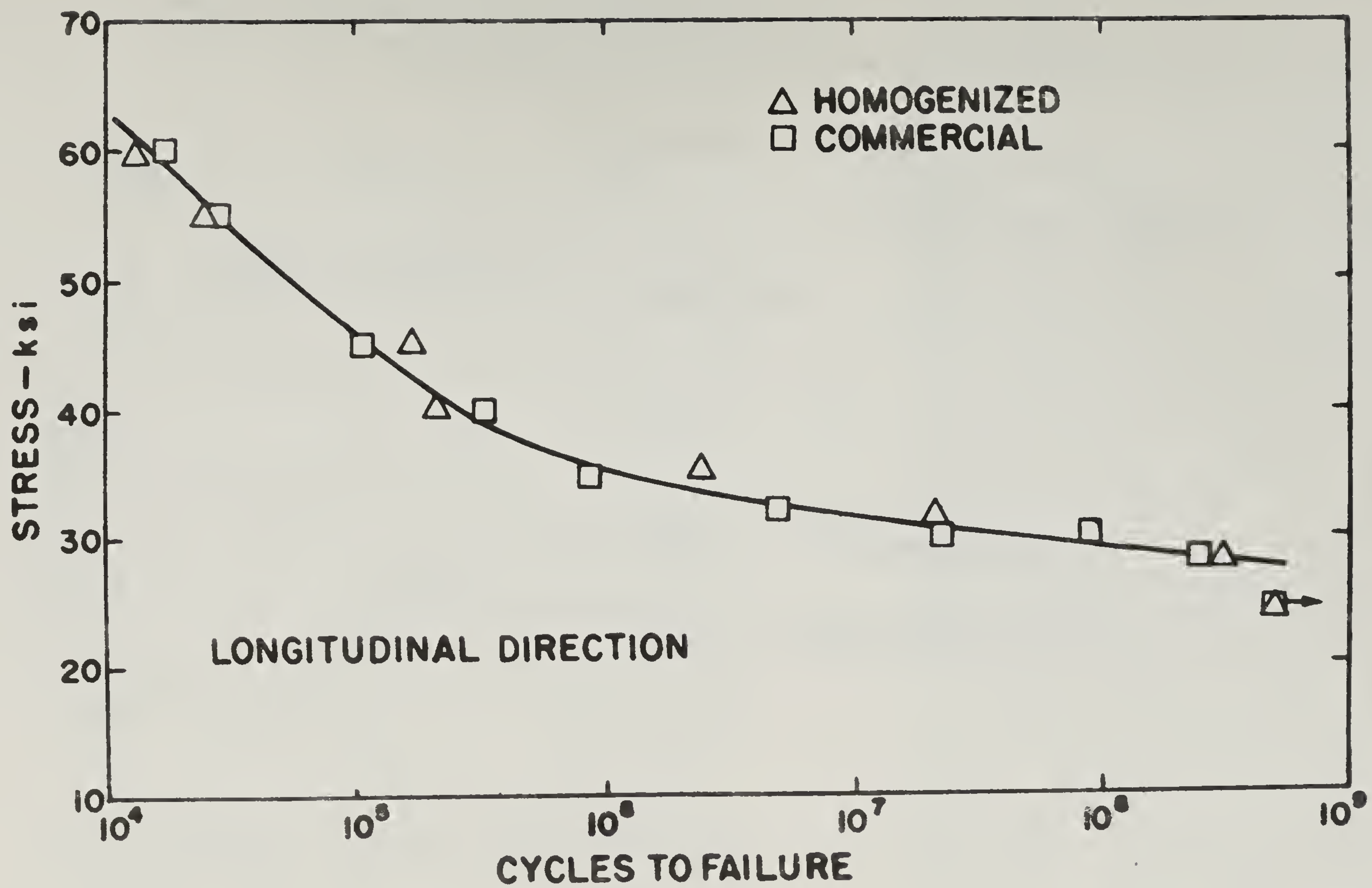


Figure 5. Longitudinal fatigue characteristics of commercial and homogenized 7075-T6 aluminum alloy. (ref. 3)

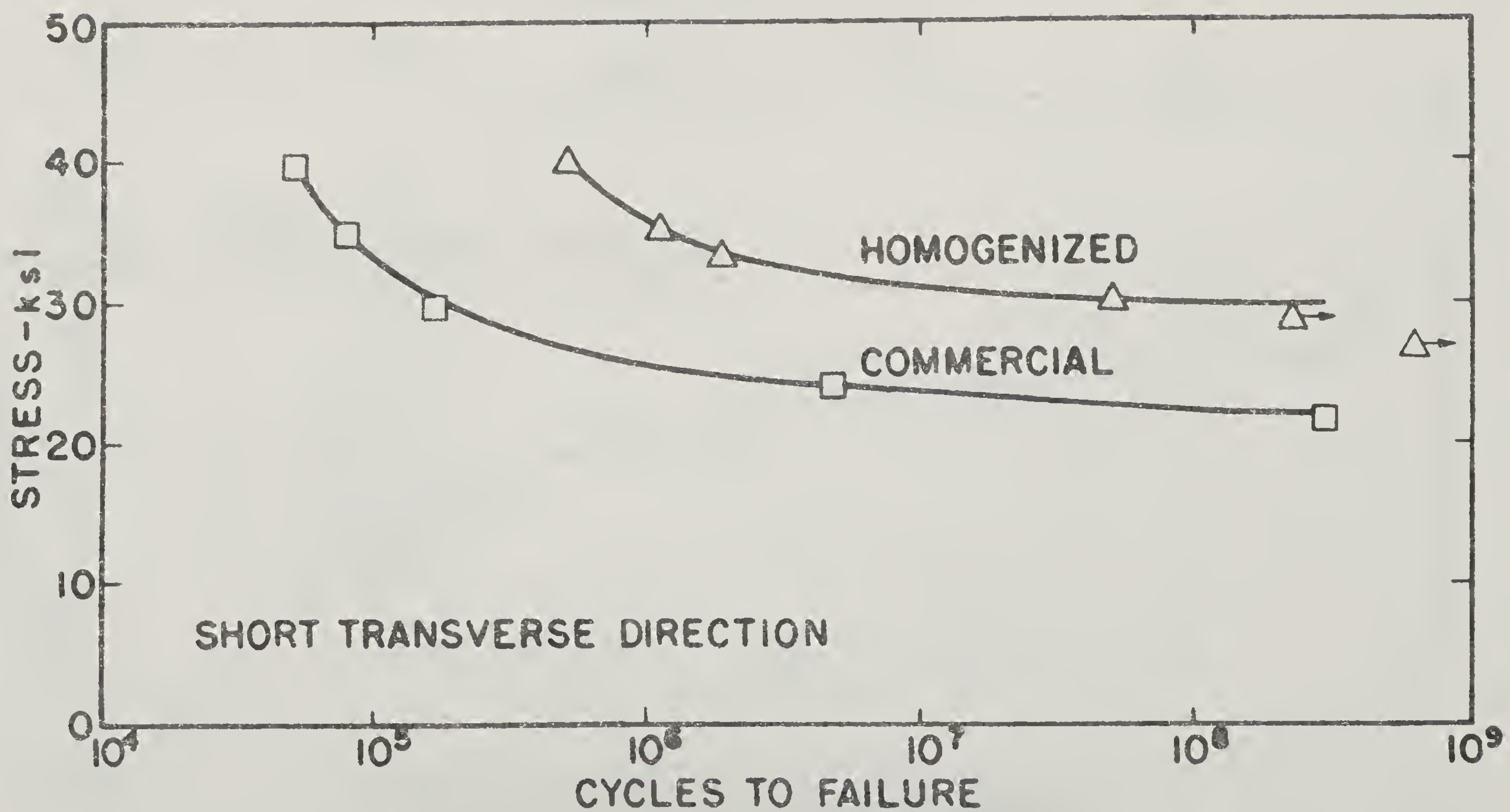
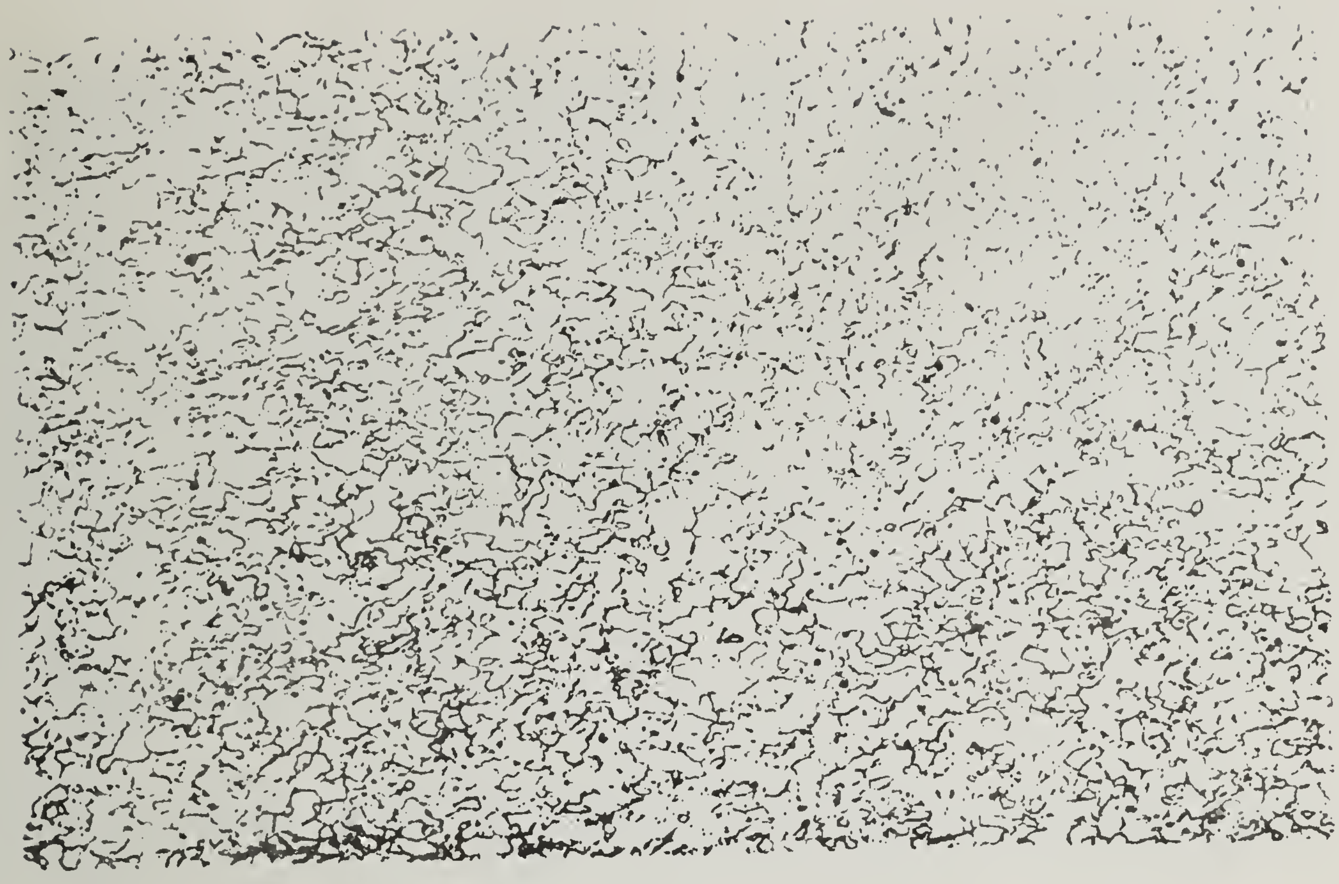
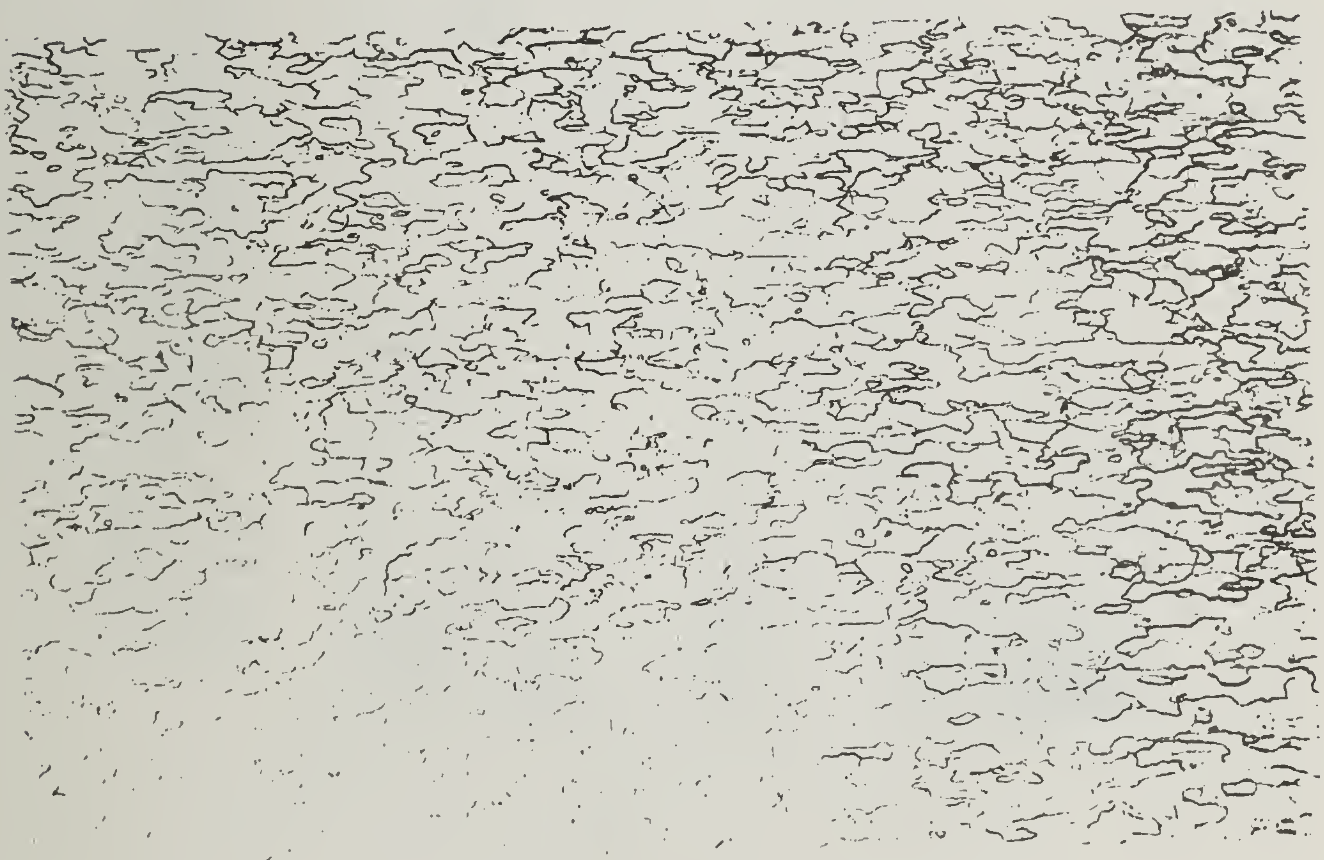


Figure 6. Short transverse fatigue characteristics of commercial and homogenized 7075-T6 aluminum alloy. (ref. 3)



(a)



(b)

Figure 7. Microstructures of ISML-ITME 7075 sheet. (a) as-recrystallized and (b) as-recrystallized + hot rolled + T6. Longitudinal sections. Mag. 100X. Keller's etch. (ref. 10, 11)

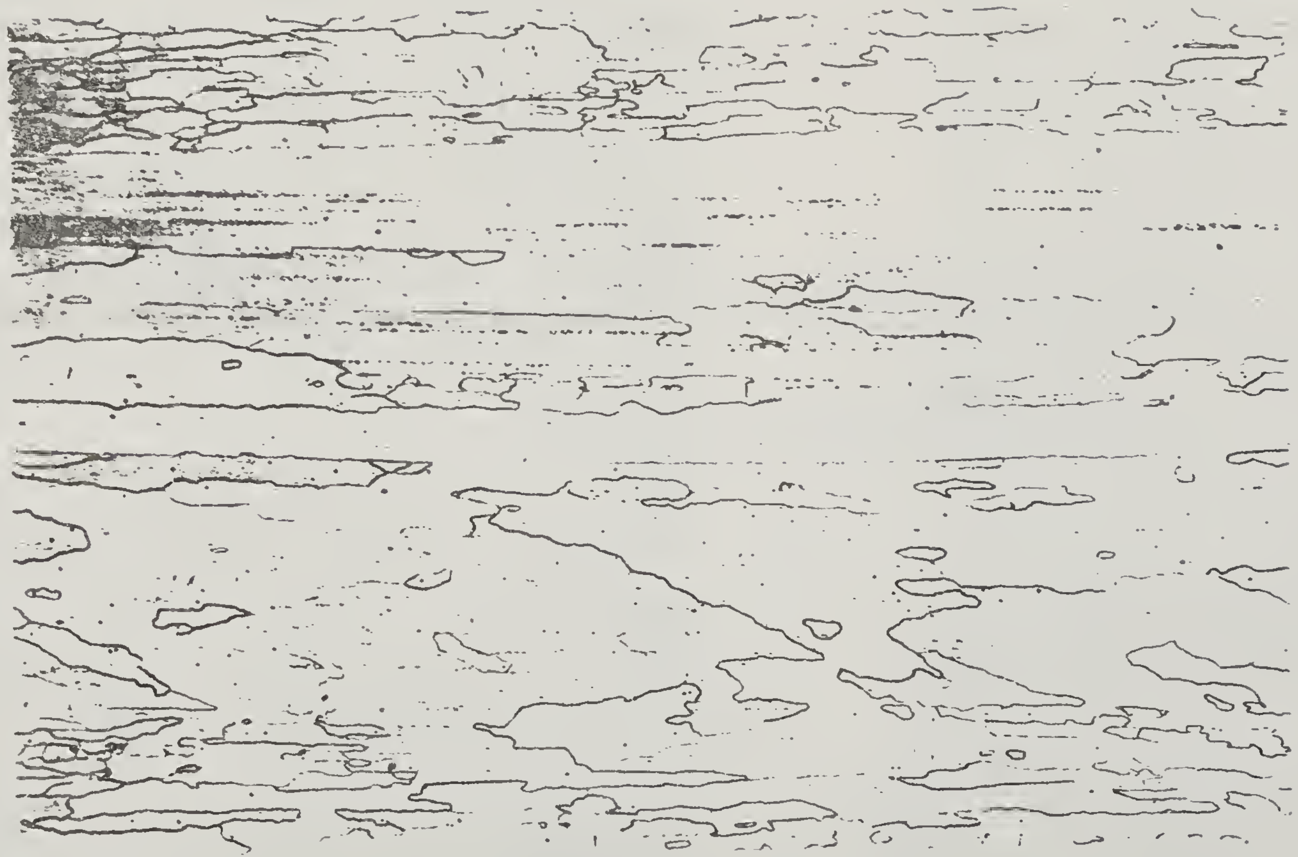
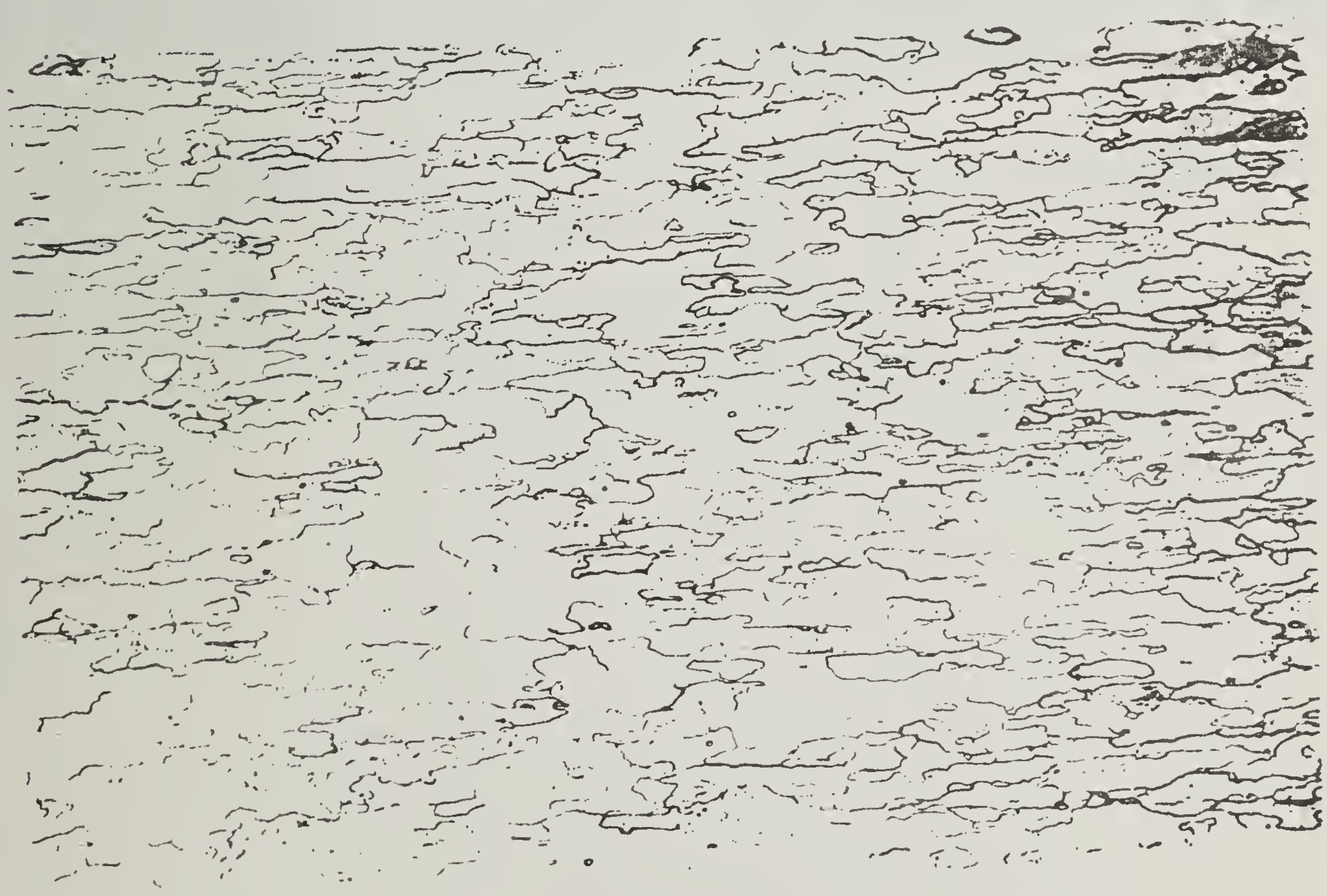


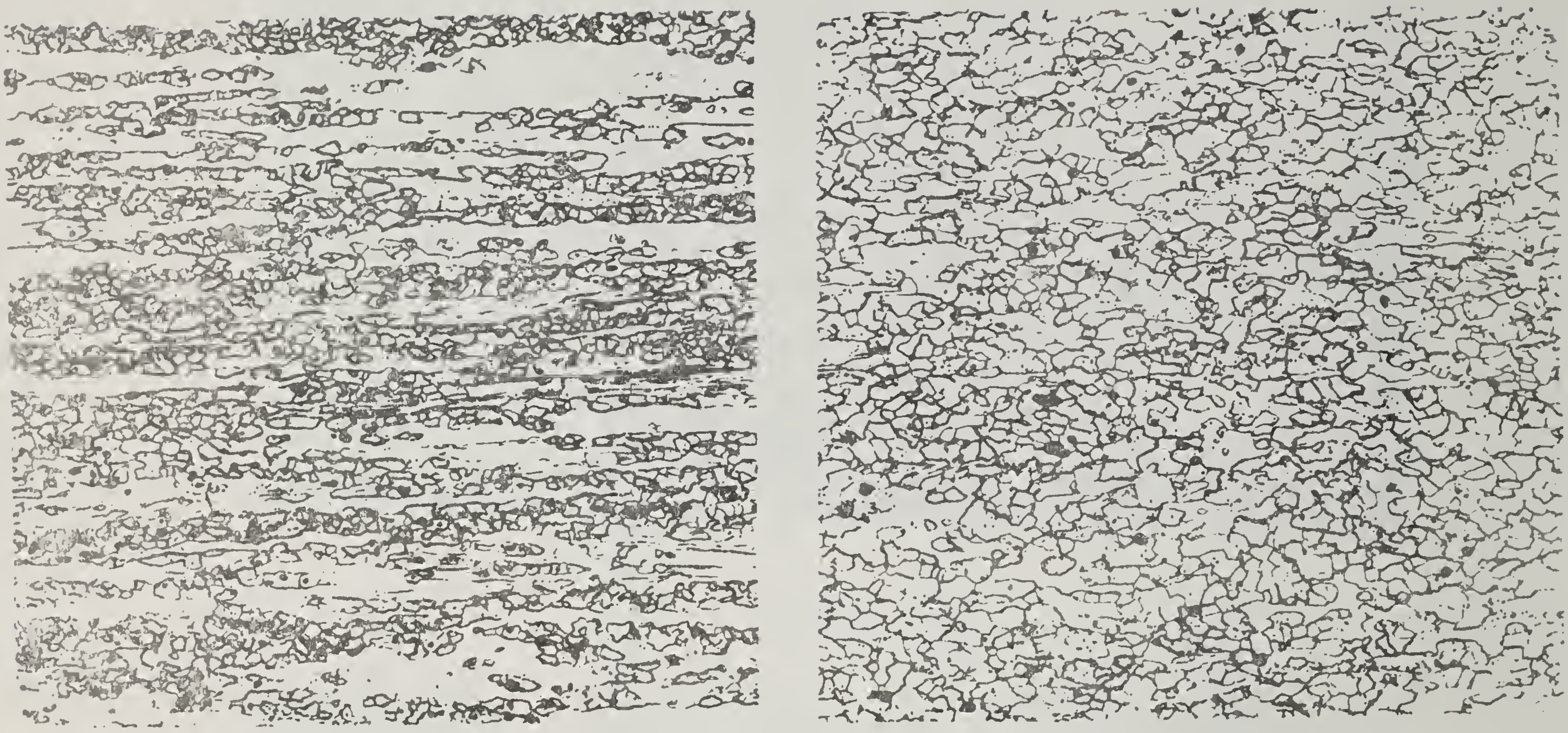
Figure 8. Microstructure of conventionally processed 7075-T6 sheet. Longitudinal section. Mag. 100X. Keller's etch. (ref. 10, 11)

(a)



(b)

Figure 9. Microstructures of FA-ITMT 7075 sheet.
(a) as-recrystallized and (b) as-recrystallized + hot rolled + T6. Longitudinal sections. Mag. 100X. Keller's etch. (ref. 10, 11)



(a) 860°F (b) 960°F

Figure 10. Microstructures of as-recrystallized ISML-ITMT 7075 1 in. thick plate. The material was recrystallized at (a) 860°F and (b) 960°F for 24 hrs and quenched. Longitudinal sections. Mag. 100X. Keller's etch. (ref. 11)

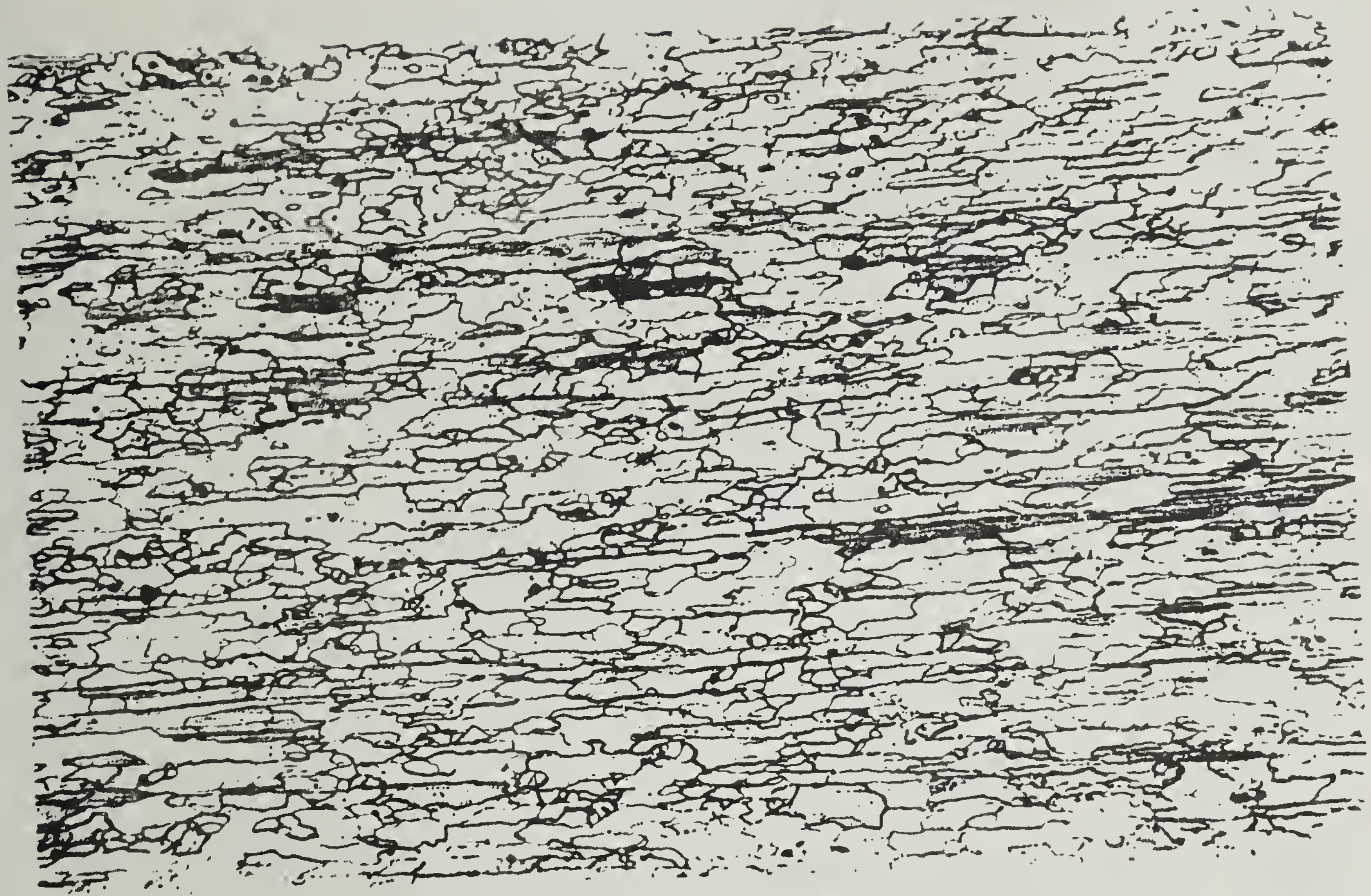


Figure 11. Microstructure of as-recrystallized FA-ITMT 7075 1 in. thick plate. Longitudinal section. Mag. 100X. Keller's etch. (ref. 11)

Figure 12. Microstructure of commercial 7075-T651 plate (1 in. thick). Longitudinal section. Mag. 100X. Keller's etch. (ref. 11)

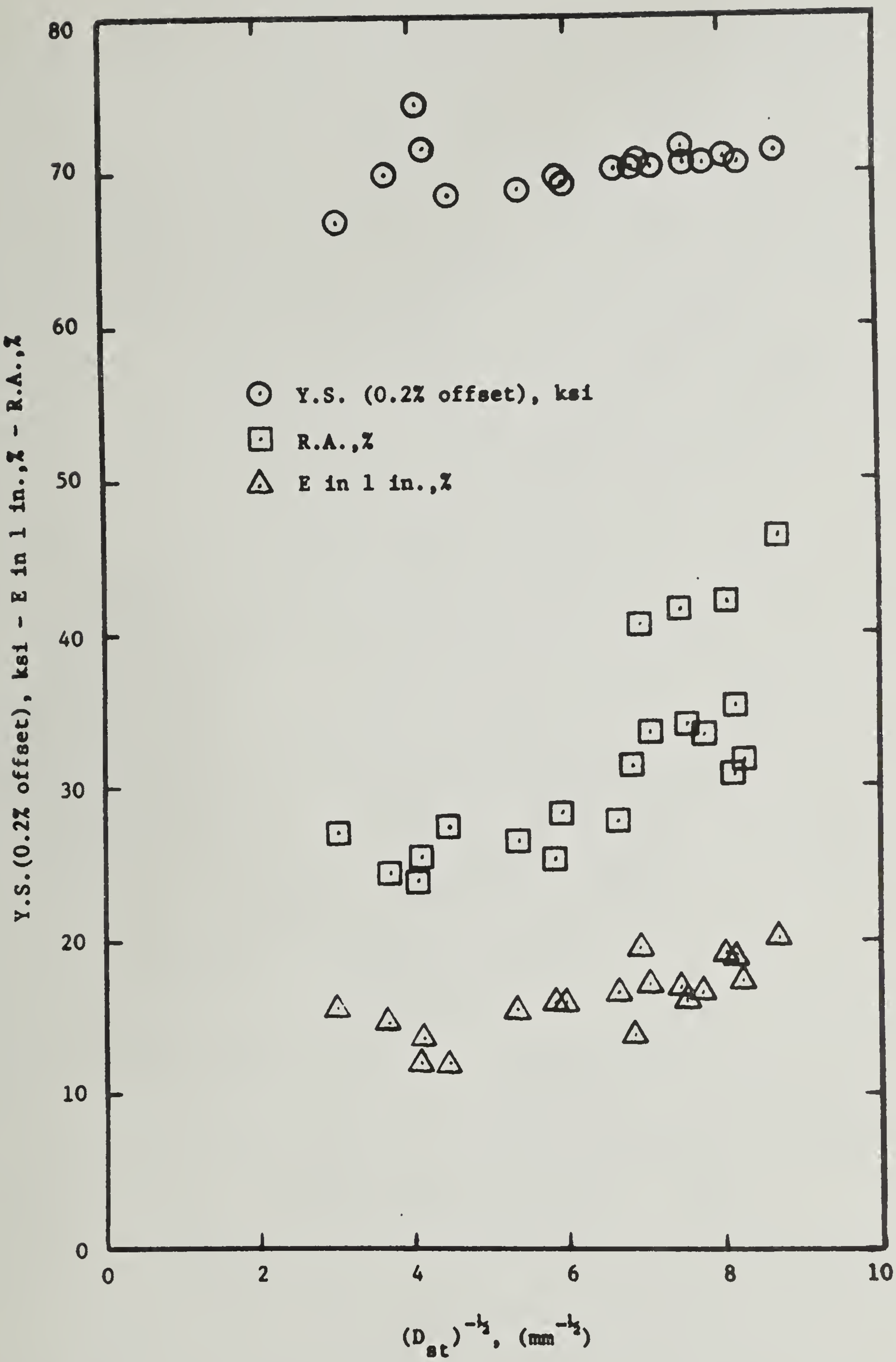


Figure 13. The mechanical properties of 7075-T6 as a function of the reciprocal of the square root of the grain size measured from a longitudinal section in a direction perpendicular to the rolling direction. (ref. 11)

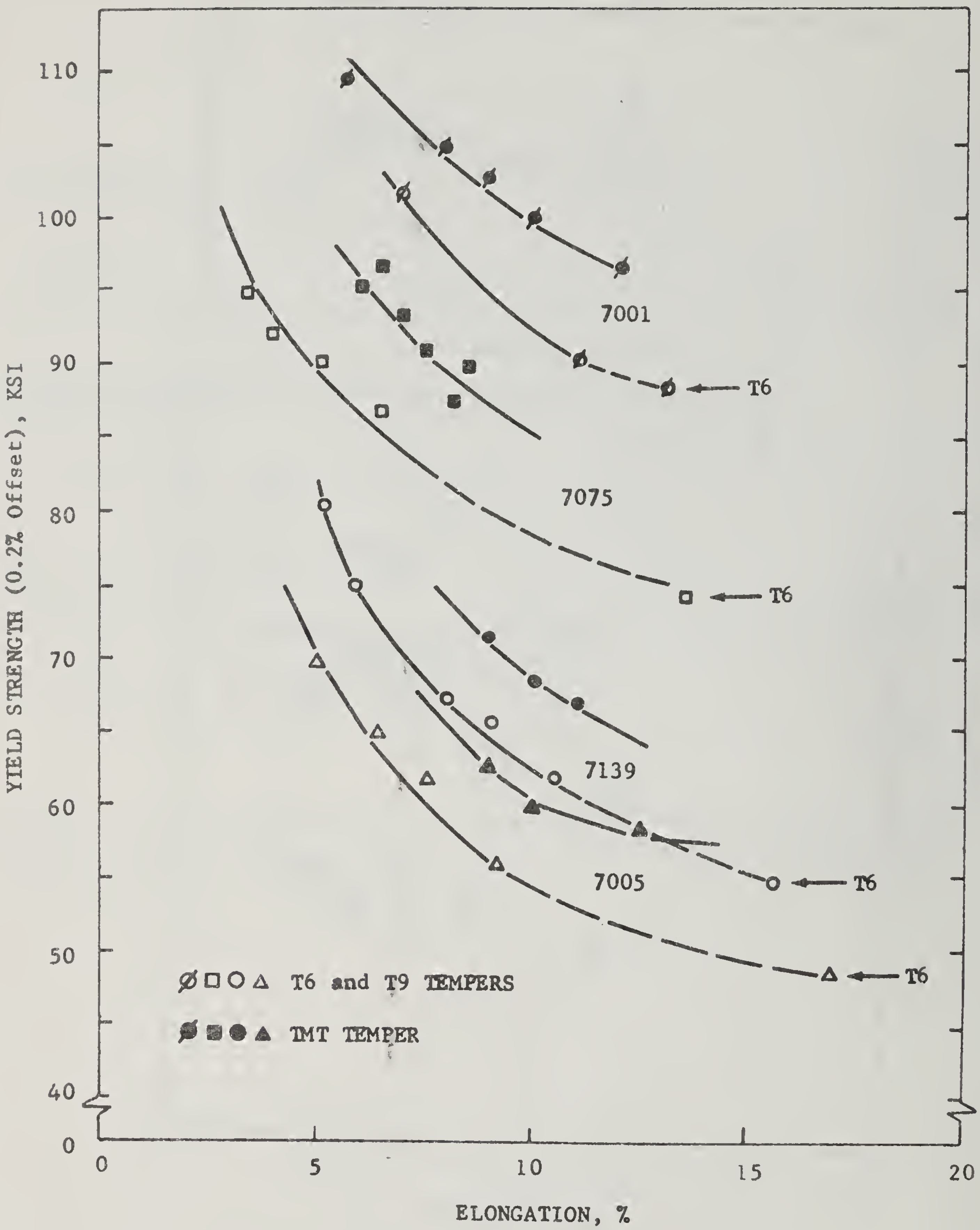


Figure 14. Yield strength and elongation of 7001, 7005, 7075 and 7139 alloys in the T6, T9 and FTMT tempers. (ref. 8, 15)